AEROSOL WORKSHOP

How Can We Use Satellite Data, Global Models and Analysis to Advance Our Understanding of Aerosol (Direct and Indirect) Climate Effects?

National Aeronautics and Space Administration

Goddard Institute for Space Studies

June 2 –3, 1997

WORKSHOP PROCEEDINGS

CONTENTS

AGENDA

WELCOME, CONTEXT, OBJECTIVES

08:30 Bob Curran: Overview of Objectives
08:45 Jim Hansen: Workshop Strategy

AEROSOL DISTRIBUTIONS AND PROPERTIES: CURRENT UNDERSTANDING

(Facilitator: John Seinfeld   Recorder: Joe Prospero)

09:00 Joyce Penner: Aerosol Climatology
09:20 Tica Novakov: Carbonaceous Aerosols
09:40 Peter Hobbs: Implications of TARFOX Data for Aerosol Climate Forcing
09:55 Ina Tegen: Soil-Dust Aerosols
10:10 John Ogren: Aerosol Single Scatter Albedo - Report on Leipzig Workshop
Break

SATELLITE AEROSOL RETRIEVALS

(Facilitator: Pat McCormick   Recorder: Ina Tegen)

10:45 Larry Stowe: AVHRR Decadal Aerosol Time Series (Pathfinder Project)
11:00 Phil Durkee: Combining AVHRR and GOES to Obtain Better Aerosol Data
11:15 Jay Herman: Quantitative Aerosol in TOMS UV Measurements
11:30 Terry Nakajima: Aerosol Optical Depth & Sizes from 2-Channel AVHRR & ADEOS/OCTS
11:45 Andy Lacis: SAGE Measurements of El Chichon and Pinatubo Aerosols
12:00 Cora Randall: POAM II Stratospheric Aerosol Data

AEROSOL EFFECTS ON CLOUDS

(Facilitator: Steve Schwartz   Recorder: Tica Novakov)

1:30 Peter Hobbs: Overview
1:55 Yoram Kaufman: Effect of Smoke Aerosol on Microphysics of Continental Clouds
2:10 Qingyuan Han: Measuring Global Aerosol-Cloud Effects
2:25 Mitsuo Uematsu: Aerosol/Chemistry Measurements Between Japan and Vancouver
Break

LINKS AMONG SATELLITES, MODELING, IN SITU AND SURFACE DATA

(Facilitator: John Ogren   Recorder: Ralph Kahn)

3:00 Steve Schwartz: Aerosol Transport Models + Satellite Data
3:15 Steve Gahn: 3-D Global Modeling with Cloud-Aerosol Physics
3:30 Alan Robock: Pinatubo Radiative Forcing and Climate Response
3:45 V. Ramaswamy: GFDL Aerosol/Climate Simulations
4:00 Tony Clarke: Role of Aircraft and Surface Data
4:15 Doug Westphal: Regional Modeling with Data Assimilation

POTENTIAL OF SATELLITES FOR FUTURE AEROSOL DATA

(Facilitator: Bill Rossow   Recorder: Kuo-Nan Liou)

8:30 Yoram Kaufman: Quantitative Aerosol Data from MODIS
8:45 Ralph Kahn: Quantitative Aerosol Data from MISR
9:00 Michael Mishchenko: Quantitative Aerosol Data from EOSP
9:15 Pat McCormick: Quantitative Aerosol Data from Satellite Lidar
9:30 Didier Tanre: Quantitative Aerosol Data from Polder

PANEL A (Direct): Aerosol parameters needed for time-dependent aerosol climatology? What is feasible?

J. Penner (Facilitator), Y. Kaufman (Recorder), T. Nakajima, L. Stowe, I. Sokolik

PANEL B (Indirect): How to quantify aerosol indirect forcing (role of satellites? modeling/analysis?)

P. Hobbs (Facilitator), S. Ghan (Recorder), T. Novakov, S. Schwartz

PANEL C (Strategy): What initiative are we proposing, what science rationale, what promises?

J. Hansen (Facilitator), M. Prather (Recorder), A. Clarke, R. Kahn, V. Ramaswamy

PANEL D (Agency Plans): R. Curran (NASA), J. Levy (NOAA), J.Moyers (NSF), R. Petty (DOE), R. Ferek (ONR)

EXECUTIVE SUMMARY

Background

A workshop on atmospheric aerosols was held at the NASA Goddard Institute for Space Studies on June 2-3, 1997. The workshop was organized by James Hansen and Robert Curran at the request of Robert Harriss, Director of Sciences of NASA's Mission to Planet Earth Office.

Atmospheric aerosols, or fine particles, could play an important role in global climate change. Natural variations of aerosols, especially due to episodic eruptions of large volcanos, are recognized as a significant climate forcing, that is, a factor that alters the planetary radiation balance and thus tends to cause a global temperature change. In addition, there are several ways in which humans are altering atmospheric aerosols, and thus possibly affecting climate. We are concerned here with the climate forcing due to changing aerosols, both the direct radiative forcing by the aerosols and the indirect radiative forcing caused by effects of changing aerosols on cloud properties. These climate forcings due to changes of aerosols are not determined well, especially in the case of anthropogenic aerosols. Indeed, aerosols are one of the greatest sources of uncertainty in interpretation of climate change of the past century and in projection of future climate change.

Harriss' reasoning was that NASA (and other agencies) already have made a large investment in space-based measurements capable of detecting aerosols, as well as investments in field campaigns and global numerical models relevant to aerosol studies. Thus he asked us to address whether a modest focused aerosol initiative could use existing capabilities to make significant progress in understanding the role of aerosols as a mechanism of climate change. He specifically asked us to address whether better use could be made of volcanic aerosols, especially the eruption of Pinatubo in 1991, to test understanding of climate change, and he emphasized a desire to encourage interagency cooperation in aerosol studies.

Science Strategy

Events strategy. A strawman science strategy, dubbed an "events" or more completely an "events in global decadal context" strategy, was proposed as an organizing principal. "Events" include natural occurrences such as volcanic eruptions and desert dust episodes, as well as long-term changes of anthropogenic emissions. The objective of this strategy is to estimate the global distribution of aerosol (direct and indirect) radiative forcing for the period of satellite data (from about 1980 to the near future) and make this available to the scientific community.

If successful, this "events in global decadal context" strategy would provide the forcing information that climate modelers need for simulations of aerosol climate effects. Quantitative aerosol forcing data, by itself, would be valuable for comparison to other climate forcings. Furthermore, aerosol changes, for example from volcanos, soil dust, biomass burning, or fossil fuel use, have distinctive spatial and temporal patterns, so there is a good chance that the aerosols produce an identifiable effect on the global four-dimensional temperature field. Thus it may be possible to detect and confirm the climate impact of aerosols.

This strategy has its best chance of success if a long continuous record of aerosol climate forcing can be constructed. A long record is best able to minimize the difficulties associated with unforced climate variability, and may be able to detect decadal change as well as interannual variability. A long record, including many specific aerosol events, also minimizes the chance of misinterpretation based on a single unusual case.

Satellite data in context of other available data. Satellites are essential for obtaining global coverage of aerosol properties. But existing satellite measurements, by themselves, are not able to define aerosol radiative forcings. Thus it will be necessary to find innovative ways to combine satellite measurements with models and with surface and in situ measurements and other data to improve information on aerosol climate forcing. For example, satellites are able to obtain more quantitative aerosol data over oceans than over land. If models of specific aerosol types can be calibrated against satellite data over the ocean, it may be possible to obtain global distributions of useful accuracy.

Climate studies depend on knowledge of the changes of individual aerosol types and sources, such as volcanos, soil dust, combustion aerosols, and so forth. As most satellite measurements cannot distinguish among aerosol types, such distinctions will require multidisciplinary analyses including the use of aerosol models. The science objectives require inclusion of all major aerosols that are changing substantially, and it is desirable that satellite analyses estimate the total change of aerosols. Because of the great difficulty in obtaining accurate aerosol change data, it seems appropriate that initial studies focus on certain aerosols that seem amenable to rapid progress or results. In this regard, sentiment was expressed by some workshop participants for early emphasis on volcanic aerosols, soil dust and perhaps smoke from biomass burning.

Fixed algorithms for aerosol parameters need to be applied uniformly to each satellite data set for their full period of record. A data processing capability needs to be established that can apply candidate aerosol algorithms and make the results available to the research community. As candidate algorithms are improved, and perhaps multiple satellite instruments employed, it will be necessary to repeatedly reanalyze the full data set.

Implementation Issues

Project structure. The task of extracting twenty-year aerosol records from satellite measurements involves substantial data processing. It will be necessary to run and rerun algorithms for the full period of measurements, and eventually to run algorithms using data from more than one instrument. NASA Headquarters will need to decide whether this is handled best using a project structure with a NASA institutional base, as one of the activities called for in the NASA Research Announcement, or in some other fashion.

Field studies. It was generally agreed that the success of this aerosol climate forcing program will depend upon complementary relevant field studies. Sentiment was expressed for design of new field experiments, but also for the fact that existing field data sets need to be more fully exploited. An issue to be decided by NASA Headquarters is when such field studies should be called for, for example whether it should be after or before initial investigator teams have been chosen for studies based on existing and planned satellite and field data. It is important that field programs be coordinated among the different agencies.

Related aerosol studies. It is important to coordinate with closely related aerosol investigations that are already supported by NASA EOS, Atmospheric Chemistry or other programs. Coordination could be aided by entraining appropriate interested individuals onto the aerosol research team described in the recommendations below, which might be accomplished by the NASA Research Announcement encouraging letter proposals for participation in the project activities with modest or no supplementary funding. An effective approach may be to have a Science Steering Group for the aerosol study project, with members selected from successful proposals and letter proposals and also including relevant program managers from other agencies.

Recommendations

The background to the Workshop's recommendations is contained in the hundreds of aerosol and climate research papers published in the past few years. The large uncertainty that aerosols introduce in our understanding of climate change is illustrated by the Intergovernmental Panel on Climate Change (*Climate Change 1994: Radiative Forcing of Climate Change*, eds. J. T. Houghton, et al., Cambridge University Press, 339 pp., 1995). The National Research Council research program plan *Aerosol Radiative Forcing and Climate Change* (J.H. Seinfeld et al., National Academy Press, 161 pp., 1995) also contains background material that is useful in establishing the rationale for our recommendations. The workshop recommendations derive in part from such background information, as well as from the individual and panel presentations, and the workshop discussions. The workshop recommendations are:

"Events" strategy. We recommend a strategic approach that leads to definition of aerosol radiative forcing on a global scale for the approximately 20-year period of satellite observations. Aerosol changes, or "events", in such a period would include natural occurrences such as volcanic eruptions and desert dust episodes, as well as long-term changes of anthropogenic emissions. It is exceedingly difficult to determine the aerosol properties with adequate precision, and there is no guarantee that knowledge of such properties will lead to definable observable climate changes, but this strategy may be our best hope for estimating and verifying the role of aerosols in climate change. It is unlikely that satellites can directly supply the required aerosol information; rather success will depend upon appropriate combinations of satellite data, models, field measurements and surface monitoring. These considerations apply to investigation of the effect of aerosols on clouds, i.e., the "indirect" aerosol climate forcing, as well as the direct aerosol forcing. We encourage collaborative efforts to define direct and indirect aerosol radiative forcings among researchers in these various specialties.

Team approach. We recommend that researchers supported by a new initiative be organized in a team to provide scientific guidance for a strategic approach toward definition of the aerosol radiative forcing, to encourage appropriate collaborations among research groups, and to provide guidance to an aerosol satellite climatology project. This "science steering group" could include researchers who are supported already for aerosol research. We recommend that such persons be allowed the option of submitting a letter proposal for little or no funding to allow them to participate in the new aerosol initiative. Also it is anticipated that the team would include experts in *in situ* data, e.g., aircraft measurements.

Aerosol "satellite" climatology. We recommend systematic application of aerosol retrieval algorithms to satellite radiances. A data processing capability needs to be established that can apply candidate algorithms to the full period of satellite measurements, rerun the full period with improved algorithms, employ multiple satellite data streams, merge satellite and aerosol model results if appropriate, and make the results available to the research community.

Aerosol types. We recommend that, to the extend practical, the aerosol climatologies be obtained for each of the major aerosol compositions. Understanding of aerosol radiative forcing depends upon data for all of the aerosol types undergoing significant change, but we recommend that first priority be given to aerosols with the most promise for contributing soon to our understanding of aerosol climate effects. Volcanic aerosols already provide two major events in the period of satellite data, and we recommend that the volcanic aerosol direct, and perhaps indirect, radiative forcings be defined more precisely. Soil dust aerosols, both natural and anthropogenic, are perhaps a major radiative forcing, but that forcing remains poorly defined; we recommend an early focus on this aerosol type. Sulfates have been a focus of study for the past few years; we recommend entraining some of these existing investigations into the new aerosol initiative. Carbonaceous aerosols are among the potentially important tropospheric climate forcings; emphasis needs to be placed on better understanding of the properties and temporal changes of organic aerosols. The science steering group should help provide scientific guidance in prioritization of research focus among different aerosol types.

Tropospheric aerosols are the principal source of uncertainty in decadal global climate change and will require the greater portion of the research effort. A relatively modest effort to complete the definition of stratospheric aerosol parameters for the past two decades can provide the climate research community with a valuable data set for aerosol climate studies.

Strategic field studies. We recommend that support be provided for strategic field studies as an integral component of the "events" strategy. Data from existing field studies can provide a starting point for modeling studies that help define uncertainties and needed observations. New field studies should be designed such that, in coordination with global satellite data and models, understanding of the direct and indirect aerosol radiative forcing is advanced; that is, field studies supported by this program should be strategic, designed to yield data leading to quantitative knowledge of aerosol direct and indirect radiative forcings.

Quantification of uncertainties. We recommend special emphasis on quantifying the uncertainty in estimated aerosol radiative forcings. Present knowledge of temporal changes in tropospheric aerosol properties is so poor that practically useful limits on the aerosol forcing are absent. The strategy for combining satellite and in situ data with global modeling must be designed to define useful limits on this forcing. Candidate aerosol climatologies must be subjected to tests, including comparisons with surface and in situ data, that confirm quantitative usefulness of the data for climate forcing applications.

Quantification of the uncertainties in the tropospheric aerosol radiative forcings is expected to emphasize the inadequacy of existing and planned satellite data per se for the climate applications. It is the required high accuracy of aerosol data for climate applications, and the need to assign portions of measured aerosol optical depths to appropriate aerosol types (sulfates, desert dust, black carbon, etc.), that demands a team approach combining satellite and in situ data with global modeling.

Interagency and international collaborations. We recommend that the initiative be carried out in collaboration with the relevant agencies and with participation of international aerosol researchers. We suggest that consideration be given to providing travel support to allow foreign researchers to participate in aerosol project and science steering group activities.

Acknowledgments. Logistical support for the workshop was provided by Katrina Parris, Sabrina Hosein, Carl Codan and Mary Larson. Funding was provided by the NASA Office of the Mission to Planet Earth. The speakers provided brief summaries of their talks for the proceedings. The proceedings were edited by Jim Hansen.

SESSION 1: OBJECTIVES AND APPROACH

Workshop Objectives

Robert Curran, NASA Headquarters

The effect of atmospheric aerosols on climate is recognized as being one of the greatest sources of uncertainty in our understanding of long-term climate change. NASA, as well as other agencies in the United States and elsewhere, have made large investments in past, current and future satellite measurements, some of the measurements being explicitly focused on aerosols.

A primary objective of the workshop is to investigate what progress in our understanding of aerosols and climate can be extracted from this existing investment. What information is missing from currently available measurements? Can other agencies or countries be expected to fill in missing data? Are there model assimilation experiments that should be carried out with existing satellite data? Can such experiments, in addition to advancing our understanding of aerosol effects on climate, help to define future sensor needs?

Secondary objectives of the workshop include taking an end-to-end look at the role of aerosols as a climate forcing. Although the focus will be on satellite data, there should be some time to address other issues. We would like to document a research approach as an input to the NASA Aerosol Research Plan. We would also like to address and coordinate with the aerosol research plans of the other agencies, to help get the most out of increasingly scarce federal science funding.

Workshop Approach

James Hansen, NASA Goddard Institute for Space Studies

The rationale for the broad scope of the workshop is the following. First, the indirect aerosol effect on climate (via changes of cloud properties), as well as the direct aerosol radiative forcing, must be considered, because the indirect effect is potentially the larger climate forcing. Second, combinations of satellite observations, in situ data, and appropriate modeling are required, because of the high precision with which aerosol and cloud changes must be specified in order to define the radiative forcing.

The scientific target of the workshop is "quantitative definition of the global distribution of aerosol (direct and indirect) radiative forcing for the period of satellite data (approximately 1980 to the near future) using satellite data, modeling/analysis and whatever else is available".

The short-term product being sought is guidance to NASA for the preparation of a NASA Research Announcement (NRA). The NRA will seek proposals which contribute to the above scientific objective. It is expected that the first stage of this research initiative will rely on available and planned satellite observations and field experiments, and that the workshop will focus on how to get more out of satellite data with the help of modeling and analysis. Thus the workshop itself will not focus on defining field measurement programs, but the research supported is expected to help define necessary future field programs that may be included in a team research approach.

Desired outcomes include: 1) bright ideas (strategies) on how to quantify (and confirm) aerosol climate forcing, 2) productive interactions/cooperation between specialized groups [satellite <=> global modeling <=> in situ data <=> small scale modeling], and 3) interagency coordination/cooperation in the implementation of a complete aerosol/climate program, including field programs and long-term monitoring.

SESSION 2: AEROSOL DISTRIBUTIONS AND PROPERTIES - CURRENT UNDERSTANDING

(Facilitator: John Seinfeld; Recorder Joe Prospero)

Aerosol Climatologies: What Modelers Need Most

Joyce Penner, University of Michigan

We now have the capability to simulate the full spectrum of aerosol types within global models: sulfate, organic carbon, black carbon, nitrate, ammonium, sea salt and dust, but there are significant differences between simulated and observed concentrations, particularly in the case of organics. It is crucial to determine the source of the organics measured in recent and past campaigns, because it introduces considerable uncertainty into the estimates of indirect forcing. If the concentration of background, natural organics is small, large estimates of indirect forcing result, but even modest increases in the background, natural aerosol can significantly reduce estimates of indirect forcing.

Direct forcing may be considerably smaller than indirect forcing, but is still not insignificant. A series of sensitivity tests with our model have shown that the uncertainty associated with the distribution of relative humidity can change our estimate of forcing (for sulfate aerosols) by 35%, while uncertainties associated with size distribution and composition (for biomass aerosols) can change estimates of forcing by 50%. There is a similar uncertainty associated with black (absorbing carbon), depending on whether it is assumed to be externally or internally mixed with other aerosol components.

We can begin to make progress in determining the total forcing by anthropogenic aerosols through a combination of comparison of these simulations with satellite data for aerosol and cloud properties and black, absorbing aerosols. Where differences are large, we will need a combination of ground-based and aircraft missions in order to determine the reasons for differences. Ground based and aircraft measurements together with modeling are needed to help understand the source of the discrepancy in predicted organics.

Carbonaceous Aerosols

Tica Novakov, Lawrence Berkeley Laboratory

The carbonaceous part of aerosol material is composed of two components: black (BC) and organic (OC) carbon. Light absorbing BC results entirely from incomplete combustion of fossil and biomass fuels. OC (principally light scattering) can be either directly produced by combustion sources or by gas-to-particle conversion of reactive anthropogenic and biogenic hydrocarbons. Information on concentration, distributions, and chemical composition of carbonaceous aerosols is sparse. Most measurement emphasized either inorganic or carbonaceous component - very few dealt with both. From surface based and recent airborne (TARFOX) measurements it is known that: OC is ubiquitously present at all locations; OC mass concentrations are comparable to and sometimes exceed sulfate concentrations; aerosol mass cannot be reconciled with inorganic species only; the carbon mass fraction may increase with altitude; OC and BC are significant contributors to light extinction; and, OC contributes to both natural and anthropogenic CCN concentrations.

This information, although fragmentary, strongly suggests that the carbonaceous aerosol component must play a role in both the direct and indirect aerosol forcing. Finally, available in-situ data are insufficient to assess temporal changes in anthropogenic carbonaceous aerosols from 1979 to present. However, known temporal changes in regional (fossil and biomass) fuel consumption might be used as a surrogate for emission modeling. Furthermore, effects of regional fuel use changes (e.g. in China and India) may be detectable in existing satellite data.

Implications of TARFOX Data for Aerosol Climate Forcing

Peter Hobbs, University of Washington

The simple paradigm that sulfate dominates aerosol column optical depth was not verified on the East Coast of the United States, where one would have thought it most likely to hold. Instead, after condensed water, organic aerosols dominated the optical depth. Similar data sets are needed for other regions to check this conclusion.

In view of the likely importance of organic aerosols, more information is needed on the vertical distribution of total (and organic and inorganic) carbonaceous aerosols, natural versus anthropogenic sources of carbonaceous aerosols, and the physical and chemical properties of these aerosols.

The following tabulated summary of initial TARFOX findings was provided after the meeting by Larry Stowe and Peter Hobbs:

Initial TARFOX Findings

- Closure obtained between computed and observed optical depth from C-131 in situ and sun-photometer data [Hegg et al.]
- Closure obtained between total aerosol mass and carbon and sulfate masses [Hegg, Hobbs and Novakov]
- Mean carbon mass fraction is about 0.5; increases with altitude [Novakov et al.]
- 66% of dry aerosol light scattering, on average, is from carbonaceous species [Hegg et al.]
- Mean albedo of single scattering of dry aerosol is 0.9 [Hegg et al.]
- Condensed water is dominant contributor to ambient aerosol optical depth. Sulfate is third, behind carbonaceous aerosol [Hegg et al.]
- Humidification factor exceeds value expected for sulfate aerosol in half the cases observed [Kotchenruther and Hobbs]
- Closure obtained between Wallops Island Raman lidar and sun-photometer measurements of optical depth at 355 nm [Ferrare et al.]
- Closure obtained between AVHRR and Wallops Island AERONET sunphotometer optical depths at 0.63 microns over six days in July, but discrepancies exist between C-131 sunphotometer and AVHRR on July 25th using the NESDIS algorithm [Ignatov et al.]
- Reasonable agreement obtained between C-131 sunphotometer and AVHRR estimates of aerosol optical depth at 0.63 microns on July 25th using the NPGS algorithm [Durkee et al.]

- Reasonable agreement also obtained with C-131 sunphotometer optical depth at 0.62 microns using the NPGS algorithm applied to GOES-8 IMAGER reflectance data, using aerosol size distribution models derived from NOAA/14 AVHRR [Durkee et al.]
- Closure obtained between computed and observed downward shortwave forcing vertical profiles from C-130 data [Hignett and Taylor]
- Upward shortwave aerosol radiative forcing sensitivity, F_{sw}, observed by AVHRR at top of atmosphere on July 25th is significantly lower than theoretical computations [Stowe et al.]

Soil Dust Aerosols

Ina Tegen, NASA Goddard Institute for Space Studies

Soil dust aerosol dominates aerosol optical thickness over large continental areas where the highest optical thickness values are measured. Our knowledge of soil dust aerosol is still limited. The global annual source strength is estimated by various authors to lie between 500 and 5000 Mt/yr, the contribution of anthropogenically disturbed soils vs. natural soils is estimated to lie between 20 and 70%, and atmospheric lifetimes can vary between hours and 14 days depending on particle size.

Knowledge of dust optical properties is crucial for evaluation of its radiative forcing and the climate effect. Different assumptions for effective size and refractive indices can cause a change in the sign of the dust forcing. Calculation of the climate effect of dust with the GISS GCM produces statistically significant cooling of the order of 1 C over large areas, but it remains to be evaluated how these values would change for different radiative parameters of dust.

Another problem is to evaluate the relationship between interannual changes in the dust load and climate modes like NAO and ENSO. We also need to separate natural variability of dust and changes in dust load by anthropogenic disturbance of soil surfaces.

Aerosol Single Scatter Albedo: Report on Leipzig Workshop

John Ogren, NOAA CMDL

A small workshop was held in Leipzig, Germany in March, 1997, to assess the current state of knowledge of aerosol single-scattering albedo (SSA) relevant to climate models. A report from the workshop has been submitted to "Contr. to Atmos. Phys." (Heintzenberg et al., 1997). Some of the main conclusions from the workshop are:

1. Source strengths used in global models of black carbon are highly uncertain, primarily because the emission factors were never intended for use in climate studies. Critically needed information on the mass fraction of submicrometer particles, the mass fraction of black carbon, and the mass absorption efficiency of black carbon in various combustion sources is greatly lacking.

2. Observational data sets on SSA are inadequate for climate studies, primarily because of uncertainties in measurements of aerosol light absorption coefficient (Bap). These uncertainties largely result from lack of a common calibration standard for Bap, and a complete lack of knowledge of the dependence of Bap on relative humidity.

3. Climate studies require knowledge of SSA to two significant figures over the range 0.8-1.0.

In the second part of my talk, I summarized the results of NOAA/CMDL's measurements of SSA. Values vary widely among the various airmass types studied (remote, marine, clean and polluted continental, and free troposphere), and even at any given site, the 75th percentile of the single-scattering co-albedo (1-SSA) was typically a factor of two greater than the 25th percentile. Especially over the continents, with their higher surface reflectivity compared to the oceans, the observed variations in SSA induce large variability in aerosol radiative forcing. As a result, it is inappropriate to represent SSA with a single value in climate studies, or in satellite data retrieval algorithms. A more appropriate approach is to consider a range of values, and calculate the sensitivity of the calculations to uncertainties in the appropriate value in SSA.

SESSION 3: SATELLITE AEROSOL RETRIEVALS

(Facilitator: Pat McCormick, Recorder: Ina Tegen)

AVHRR Decadal Aerosol Time Series (Pathfinder Project)

Larry Stowe, NOAA NESDIS

Thirteen years (1981-1993) of September monthly mean values of aerosol optical thickness, AOT, at 0.63 microns and cloud-free broadband reflected flux, F_{sw}, at the top of atmosphere for ocean grid cells (110 km resolution) have been used to estimate the maximum shortwave aerosol forcing observed by AVHRR over this period. A map of variance explained by linear regression (r**2) of F_{sw} as a function of AOT over the thirteen years showed that primarily grid cells in the region from about 20S to 30N exhibited an aerosol forcing signature sufficiently large to be detected by AVHRR (i.e., regions where r**2 > 30%). In this region, the maximum monthly mean aerosol forcing [F_{sw}(year of AOT_{min}) - F_{sw}(year of AOT_{max})] was negative ranging between -10 and -40 Wm^{-2}. Maps of the maximum change in optical depth (AOT_{max} - AOT_{min}) over the thirteen years suggest that this forcing is due to the combined effects of stratosphere aerosol from Mt. Pinatubo and biomass burning aerosol over Indonesia and west of tropical Africa and South America ($0.2 < \Delta AOT < 1.0$). It is likely that for other months of the year, aerosol forcing signals would be detected with the PATMOS datasets in other regions and at higher latitudes associated with Saharan dust outbreaks and industrial pollution. It is proposed that these observations be used to test the performance of climate models in simulating "aerosol events" over this thirteen year period.

Combining AVHRR and GOES to Obtain Better Aerosol Data

Phil Durkee, Naval Postgraduate School

Aerosol optical retrievals from polar-orbiting satellites generally offer higher spatial, radiometric and spectral resolution than geostationary satellites. The NOAA POES series nominally provides two views per day of a region at nearly constant local times. Geostationary satellites provide imagery at up to 15 minute resolution. The GOES 8/9/10 visible channel offers sufficient radiometric resolution to retrieve aerosol optical depth but lacks other wavelengths needed to account for particle size variations and subsequent effects on directional scattering.

A technique that combines POES and GOES can provide aerosol optical depth at high temporal resolution while accounting for variations in directional scatter. This technique compares favorably to POES retrievals and airborne sunphotometer measurements.

Use of GOES in optical depth retrievals will greatly improve analysis of aerosol radiative forcing in an “events” strategy. Plumes from aerosol sources can be tracked at high temporal resolution. This will greatly aide in identifying source regions, vertical distributions, transport processes and diurnal forcing. In addition, GOES analysis can provide regional mean scattering phase function characteristics from observations at varying sun-earth-satellite geometry.

TOMS UV Measurements of Aerosols

Jay Herman, Goddard Space Flight Center

TOMS can observe both absorbing (smoke, dust, volcanic ash) and small-particle nonabsorbing aerosols (sulfates etc.) over land and water. We have a daily global record of aerosols from 1979 to the present. Recently the observed aerosol index has been converted to optical depth and compared with sunphotometer data. The observations show that the TOMS aerosol index is linearly related to the sunphotometer optical depth with the slope corresponding to different aerosol types. The form is (for absorbing aerosols): Aerosol Index = Ki □(1 - w) (1 - P), where Ki = slope, w = single scatter albedo, P = pressure in atmospheres, □= optical depth.

Time series for nonabsorbing aerosols show the strong sources from the U.S. eastern region and over western Europe. The amount of nonabsorbing aerosols decreases rapidly with latitude with almost no nonabsorbing aerosols in the Southern Hemisphere. The nonabsorbing aerosol index is given by Aerosol Index = Ci (□340 - □380)

Aerosol Optical Depth and Size from 2-Channel AVHRR and ADEOS/OCTS

Terry Nakajima, University of Tokyo

Aerosol optical properties. An efficient algorithm has been developed for retrieving the aerosol optical thickness and Angstrom exponent from channel-1 and -2 of AVHRR (Nakajima and Higurashi, *J. Geophys. Res.*, in press, 1997; Higurashi and Nakajima, An analysis of radiative fields in a coupled atmosphere-ocean system, International Radiation Symposium, University of Alaska, Fairbanks, August 19-24, 1996). It is found that the set of the aerosol optical thickness and Angstrom exponent can show a distinct features of difference in the airmass origin on global scale. The Angstrom exponent significantly increased over large areas of several hundred kilometers extent around industrial areas and biomass burning regions; small values are found in the most areas of oceanic atmospheres and areas loaded by dust particles. Combining the present results with the absorbing aerosol characteristics derived from TOMS UV analyses is a promising approach for improving our knowledge of the global distribution of aerosol optical properties.

Cloud microphysical parameters. The algorithm of Nakajima and Nakajima (*J. Atmos. Sci.*, **52**, 4043-4059, 1995) has been extended for global analyses. The results show a similar characteristics of the effective cloud particle radius as found by Han *et al.* (*J. Climate*, **7**, 465-497, 1994), i.e., the effective particle radius is larger over ocean areas than over land areas. It is found, however, our values are systematically larger by about 2 micron than those of Han *et al.* (1994) for a case of 1988. Calibration constants of AVHRR might be the cause of the difference.

The following strategies are important for future aerosol studies:

(1) *Satellite-guided experiments.* There are characteristic regions where the in situ aerosol chemical and optical properties should be studied to confirm and validate the retrievals from AVHRR two channel and TOMS UV algorithms.
(2) *Homogeneous time series of aerosol parameters.* It is important to define good aerosol-related parameters which can be retrieved from 14 year satellite records of AVHRR and TOMS. Those parameters should be simple enough to be retrieved homogeneously on global scale from existing satellite radiance data.

SAGE Measurements of El Chichon and Pinatubo Aerosols

Andrew Lacis, NASA Goddard Institute for Space Studies

A global climatology of stratospheric aerosol radiative properties has been compiled from SAGE II multiwavelength extinction measurements for the period 1984-1994 (Thomason and Poole, *JGR*, **102**, 8967-8976, 1997). With the assumption that the aerosol composition is adequately represented by 75% solution of H2SO4 (based on in situ measurements by Deshler *et al.*, *GRL*, **20**, 1435-1438, 1993), the aerosol optical depth and effective radius can be accurately retrieved, based on Mie scattering. Because the SAGE measurements do not have a sufficiently broad spectral baseline to constrain the size distribution variance, the effective size distribution variance is instead inferred from ISAMS limb scan measurements at 12.1μm (Lambert *et al.*, *GRL*, **20**, 1287-1290, 1993). The size distribution variance, while it has little impact on the spectral extinction at visible wavelengths, has substantial impact on the amount of extinction at thermal wavelengths, which account for most of the stratospheric heating produced by volcanic aerosols. Based on these measurements, a monthly-mean stratospheric aerosol climatology of optical depth and particle size with 4°x 5° horizontal and 5 km vertical resolution has been developed for GCM use (Hansen *et al.*, *NATO ASI Series*, **142**, 233-272, 1996). The GCM-simulated global surface cooling of about 0.5°C, and stratospheric warming of several degrees, are in basic agreement with observed surface and stratospheric temperature changes (Hansen *et al.*, *GRL*, **23**, 1665-1668, 1996; Angell, *JGR*, **102**, 9479-9486, 1997). This provides a closure between the observed radiative forcing, the climate model simulation of the climate response, and the observed real world climate response.

POAM II Stratospheric Aerosol Data

Cora Randall, University of Colorado

The POAM satellite instruments series is similar in concept to SAGE, measuring aerosol extinction profiles at 5 wavelengths from 0.353 to 1.06 microns. POAM II (Oct. 1993 to Nov. 1996) and POAM III (to be launched in January, 1998) make measurements in polar regions, OOAM (to be launched in August, 1997) makes measurements at mid and low latitudes.

POAM II measurements compare well with coincident SAGE II observations, and extend the SAGE measurements to higher latitudes year-round.

The POAM II and POAM III polar measurements extend the SAM II aerosol measurements into the post-Pinatubo era, and can provide additional parameters such as volume density, surface area density, effective radius and number densities (with appropriate assumptions regarding size distribution functions). OOAM provides the same data for mid and low latitudes.

The combination of POAM III, OOAM and SAGE III (and SAGE II if still operational) solar occultations, and SAGE III lunar occultations will provide unprecedented global coverage of aerosol vertical profile measurements. Transmission profiles for these instruments should reach the mid-troposphere.

Limb occultation measurements such as those of the POAM and SAGE instrument series are the best means of deriving climatologies of sub-visual cirrus clouds.

Recommendations: These mainly stratospheric data should be utilized to the fullest advantage to understand aerosol climate forcing effects during volcanic periods. They should further be used in conjunction with the column measurements such as TOMS and AVHRR to separate tropospheric aerosols from stratospheric aerosols (or to separate low troposphere from high troposphere, when the transmissions permit). Climatologies of cirrus clouds should be expanded to include on-going measurements and measurements at high latitudes (see note below).

Note: Regarding subvisual cirrus clouds: It was not clear from the workshop discussions if these were deemed important with regard to climate forcing. What is the general opinion on this issue? We did not have time to discuss the capabilities of limb occultation measurements regarding cirrus cloud detection; but if the general agreement is that they play an important role in the indirect forcing, I think we should include efforts to use limb occultation measurements to document their climatology and year-to-year variability in any recommendations made to NASA.

Note: I have been asked about availability of aerosol date from SME (Solar Mesospheric Explorer). If making that data public in a useable form is a priority for modelers, we can pursue this at LASP to see what resources it would require.

Session 3 Summary by Recorder (*Ina Tegen*)

This session provided an overview of currently available satellite retrieval methods to obtain global aerosol distributions for the period from the beginning of the 1980's until present. Retrieval methods to obtain tropospheric aerosols (from AVHRR, GOES, TOMS) and stratospheric aerosols (SAGE, POAM II) were presented. Although quantitative retrieval of tropospheric aerosol distributions and properties is difficult, those products may provide useful information if combined with each other, in-situ measurements, and global modeling results. The combination of information from several channels and different satellites (geostationary and polar orbiting) appears to be a promising approach for obtaining quantitative information about tropospheric aerosols. Some starting points for derivation of information about aerosol processes and interannual changes from those retrievals were presented.

Larry Stowe estimated aerosol radiative forcing changes at low and middle latitudes from his AVHRR aerosol product for the month of September. He found an optical thickness of about 0.2-0.3 due to Pinatubo aerosols and 0.7 near Indonesia due to biomass burning. The latter was estimated to cause a regional forcing of -10 to -40 W/m^2. Near the United States East Coast (location of the TARFOX experiment) a positive forcing of 20-30 W/m^2 was found. For most regions the tropospheric aerosol effect was too small to be detected by this method. He indicated that other months would probably have measurable tropospheric forcings due to dust and industrial pollutants, as concentrations of these aerosols are not at their maximum in September.

Discussion after Stowe's paper:

Question: How would an error in the assumption of the aerosol absorption change the results?

Stowe: An error in the assumption of the imaginary part of refractive index would lead to errors of only 20% in these retrievals. Also, even if errors in the retrievals occur due to too many assumptions, interannual changes in aerosol patterns can be recognized.

Phil Durkee showed measurements taken during a TARFOX flight (east coast of United States), which combined results from the polar orbiting AVHRR instrument and the geostationary GOES satellite. Intercomparison with sunphotometer measurements (4 wavelengths) showed good agreement for optical thickness. Retrieved optical thickness values ranged between 0.2 and 0.3.

While GOES provides a substantially better temporal resolution than AVHRR (of the order of hours compared to days), the spectral resolution from AVHRR is necessary to provide additional information about aerosol properties. An important point in satellite AOT retrievals is the use of the correct aerosol model - it turns out that when tested with 2 phase functions the results can vary by a factor of 3 with the scattering angle.

Discussion after Durkee's paper:

Question: Does the change in phase functions depend on the assumed particle size?

Durkee: Yes, size was allowed to vary in the retrieval; refractive index was held constant.

Question: Is it possible to find one 'best' phase function?

Durkee: It is unlikely that all parameters will ever be accurately defined, uncertainties must be expected. But the actual range in radiances is smaller than would be implied by phase function differences.

Jay Herman presented retrievals for both absorbing and non-absorbing aerosols for the period of 1979 onward based on TOMS measurements. For absorbing aerosols (dust and carbonaceous particles) the TOMS product gives an 'Aerosol Absorption Index' for land and ocean regions.

Some limitations of the absorbing aerosol product are that no absorbing aerosols can be detected close to the ground (below 1.5 km) and under cloudy conditions sensitivity is reduced. For non-absorbing (sulfate) aerosols the sensitivity is less than for absorbing aerosols, and interference of surface reflection occurs.

Case studies at some specific sites show that at Tenerife the aerosol index peaks in January, which is caused by aerosol transport rather than source strength at this time of year. In Spain, on the other hand, the non-absorbing aerosol which is caused by in-situ aerosol production is stronger than the absorbing (Saharan dust) which is caused by in-situ aerosol production. In South America the absorbing aerosol background signal is small, the biomass burning signal is found to be negatively correlated with rainfall.

Comparison with in-situ sunphotometer data shows a generally high positive correlation between AOT and TOMS absorption index.

Terry Nakajima described a 2-channel retrieval method which provides information on aerosol size as well as optical thickness. Explicit information on aerosol composition in not provided by this method, although in some cases it can be inferred from aerosol history.

His results show that, for biomass burning particles, South American aerosols appear to have different properties than South African aerosols, specifically differing in size.

In areas influenced by air masses from industrial regions particles are smaller at higher optical thicknesses, while for very high optical thicknesses at some locations the particle sizes are larger because of hygroscopic growth.

Comparison of cloud and aerosol optical thicknesses and particle sizes shows no correlation between cloud optical thickness and aerosol optical thickness on a global scale.

Discussion after Nakajima's paper:

Question: How do the results for cloud particle sizes compare to the results of Han and Rossow?

Nakajima: The results have a similar magnitude.

Question: For the case of soil dust aerosol, can a difference in particle size be observed for different distances from the source regions?

Nakajima: No, such a size change was not observed.

Question: Can interannual changes be observed in these retrievals?

Nakajima: Only one year (1991) has been analyzed so far.

Andy Lacis described aerosol information extracted from multispectral SAGE data. Specification of the radiative forcing requires knowledge of the aerosol effective size, vertical distribution and refractive index. Spectral extinction ratios are sensitive to particle size, and as a result, if the size distribution is monomodel, lookup tables can be devised to determine effective size from the spectral extinctions. With the size information optical thicknesses can be derived at other wavelengths. Although bi-model size distributions may be more realistic for stratospheric aerosols, the use of such distributions was not found to improve the overall fit with observations.

For calculations of the aerosol effect in a GCM the aerosol optical thickness and effective radius are needed as input. In the GISS GCM it is found that the main local effect of the aerosols is stratospheric heating via absorption of thermal radiation, the solar contribution being relatively smaller.

Discussion after Lacis' paper:

Question: Are the retrieved sizes vertically resolved?

Lacis: No, in the present retrieval they are the column average.

Question: Will Sage III improve the accuracy of stratospheric aerosol retrievals?

Lacis: Yes, for several reasons, but especially because of somewhat broader spectral coverage.

Cora Randall described 'POAM II Polar Ozone and Aerosol Measurement) stratospheric aerosol data. The measurement concept is similar to that of SAGE. POAM II has 1km resolution at 15-30 km altitude. Observations from this instrument exist for the years 1994-1996. Comparisons with SAGE in this period show good agreement. POAM II shows that lower aerosol extinction occurs inside of the polar vortex.

Two follow-up instruments will be launched: OOAM (1997), POAM III (1998).

SESSION 4: AEROSOL EFFECTS ON CLOUDS

(Facilitator: Steve Schwartz; Recorder: Tica Novakov)

Aerosol Effects on Clouds: An Overview

Peter Hobbs, University of Washington

In view of the potential importance of the indirect (cloud) effects of atmospheric aerosols in radiative forcing, it is essential that studies be carried out to quantify these effects.

This will require highly focused field studies to: 1) Improve understanding of the relevant cloud physical processes. 2) Validate the assumptions and algorithms used for deriving aerosol parameters from satellite measurements. 3) Provide inputs to GCM models. A field project that could provide important information on all three of these issues is outlined later in this report by Panel B (Indirect Aerosol Forcing).

Effect of Smoke Aerosol on Microphysics of Continental Clouds

Yoram Kaufman, Goddard Space Flight Center

Analysis of 1 km AVHRR data from South America is used to retrieve smoke optical thickness and cloud drop size and reflectance. The results are summarized on a one degree by one degree grid. Increase of smoke optical thickness from 0.2 to 0.8 decreased drop size from 14 to 8 microns, reduced reflectance from 0.71 to 0.68, but (increased) ?? 0.35 to 0.45. The effect on clouds depends on the latitude or on precipitable water vapor amount. This method increases to a maximum the range of effects that we observe, far above noise and calibration problems. It requires 1 km resolution data.

Recommendation: 1) Save and restore all "old" AVHRR 1 km data, 2) Apply this method on specific regions, detecting the correlation of aerosol optical depth, cloud droplet radius and cloud reflectance; examine effects of cloud height and meteorological conditions, 3) Measure the relationship between CCN, SSA, size distribution and optical thickness, 4) Generate models that simulate this interaction of aerosols and clouds.

Measuring Global Aerosol-Climate Effects

Qingyuan Han, University of Alabama

A global survey of the relationship of cloud albedo and liquid water path with droplet size using ISCCP data shows that cloud albedo increases with decreasing droplet size for most clouds over continental areas and for all optically thick clouds, but that cloud albedo decreases with decreasing droplet size for optically thin clouds over most oceans over tropical rainforest regions. For almost all clouds the liquid water path increases with increasing cloud droplet size. The pattern of cloud droplet column concentration shows more clearly the effect of aerosol concentration variation on clouds. It exhibits the expected increase of droplet column concentrations between ocean and continental clouds and in tropical areas during dry seasons where biomass burning is prevalent. Cloud susceptibility has been retrieved on a global scale and the result reveals that cloud susceptibilities around most continental areas are close to zero. For remote ocean areas, the susceptibility is very large, suggesting locations where the largest aerosol indirect effect may occur. Correlations of aerosol optical thickness over oceans with cloud droplet size, cloud column droplet concentration and cloud albedo show variations depending on region and season.

This study suggests that many aspects in the study of the aerosol indirect effect can be performed using satellite observations. It also illustrates that assumptions used in model studies need to be verified with observations on a global scale. Further progress in understanding the aerosol indirect effect can be made through close collaboration between model studies and satellite observations.

Measurement of Mineral and Anthropogenic/Biogenic Aerosols Over Northern North Pacific

Mitsuo Uematsu, University of Tokyo

One dust event in Japan revealed two peaks of particle size concentration. Chemical composition of the dust from the Asian continent was obtained by direct filter sampling and individual particle analysis with SEM and EDS. The dust event lasted about 20 hours. Small anthropogenic aerosols appeared first, then large mineral aerosols arrived.

It is difficult to observe aerosols from satellites over the northern North Pacific due to high cloud cover, but the region is interesting for aerosol studies because of the high biological activity and anthropogenic effects on aerosols. Pronounced seasonal variation of mineral and anthropogenic/biogenic aerosols were observed from a cargo ship traveling regularly between Japan and North America. The air masses sampled are affected by transport from the Asian continent and in some cases from North America.

Removal of mineral particles occurs in the marine atmosphere below cloud via wet scavenging, suggesting that mineral aerosols may not be important for the indirect effect. It is interesting to note that mineral particle was dominant as insoluble particle in the spring rains, but carbonaceous particles, with diameter less than a micron, were present heavily in the summer rains.

SESSION 5: LINKS AMONG SATELLITES, MODELS, IN SITU AND SURFACE DATA

(Facilitator: John Ogren; Recorder: Ralph Kahn)

Aerosol Transport Models + Satellite Data

Steve Schwartz, Brookhaven National Laboratory

Published chemical transport models for aerosols or for specific aerosol species such as sulfate, especially those that are driven by monthly mean winds from climatology, exhibit smooth contours. The repeated publication of figures showing such smooth contours may have prejudiced thinking that this is in some way representative of the actual distribution of aerosol loadings. Seasonal composites of satellite-derived aerosol optical depth likewise exhibit rather smooth contours. Reality is very much otherwise. The short residence times of tropospheric aerosols are comparable to the time scale of variability in synoptic scale winds and precipitation that control the distribution of aerosols. This situation, together with the highly nonuniform distribution of sources of anthropogenic and dust aerosols, leads to a highly heterogeneous distribution of aerosol loadings (in great contrast to the rather smooth distribution of the long-lived greenhouse gases). The heterogeneity in aerosol loadings is readily manifest in time series of aerosol loadings at a given location. Likewise one should expect a similar variation in the spatial distribution, as is exhibited in models for which the controlling meteorology exhibits the short-time variability of actual synoptic scale variability, but the synoptic observational coverage required to develop this picture is lacking (one might imagine trying to get this from GOES, although the photometric resolution is marginal). Models can be highly valuable in trying to discern the aerosol loading in observations, provided they accurately represent the temporal heterogeneity that is responsible for the heterogeneity in loadings. For this it is necessary to drive the model by observation-derived meteorological data, not by climatological or GCM meteorology. This situation may be turned to advantage, because the inherent spatial and temporal variability of aerosol loading allows the possibility of experiments that can discern and quantify the aerosol influences, by comparisons between high and low loading situations.

Three-Dimensional Global Modeling with Cloud-Aerosol Physics

Steve Ghan, Pacific Northwest Laboratories

To facilitate comparison between simulated and observed aerosol, all aerosol models should be either driven by observed meteorology or by a GCM that is nudged toward observed meteorology.

Aerosol radiance (the difference between the true radiance and the radiance if aerosols were not present) should be used to evaluate aerosol models. Use of aerosol optical depth is not as closely related to aerosol radiative forcing and introduces uncertainties in the “observations”.

There does not appear to be any way to determine cloud droplet number concentration from current or planned satellite measurements. The combination of a mm cloud radar and a microwave radiometer on a satellite would fulfill this critical need for estimating indirect radiative forcing.

Pinatubo Radiative Forcing and Climate Response

Alan Robock, University of Maryland

Scientists use a variety of definitions of "Radiative Forcing." What the climate system actually feels is in situ radiative heating of the atmosphere and changes of net shortwave and downward longwave flux at the surface. All radiative forcings should be evaluated in these terms to compare them. This can be illustrated by looking at the effects of Pinatubo aerosols on visible, near-IR, and thermal IR in both the troposphere and stratosphere.

Stenchikov *et al.* (Max Planck Inst. fur Meteorol., Rept. 231, Hamburg, 40 pp., 1997; submitted to *J. Geophys. Res.*, March 1997) developed a detailed data set of stratospheric aerosol properties and distribution for the 2-year period following the 1991 Pinatubo eruption and produced heating rates and fluxes from the data, using the Max Planck Institute ECHAM-4 GCM. We suggest that other GCMs use these same data sets (aerosols, or heating rates and fluxes) as forcing, to compare the radiation schemes and climate response. Stratospheric aerosols should be an important part of the NRA, as they offer important episodic (event-based) forcings which are important for the climate system.

Factors Governing Aerosol Radiative Forcing

V. Ramaswamy, NOAA Geophysical Fluid Dynamics Laboratory

A principal factor affecting aerosol radiative forcing is the dependence on humidity. Thus far, most if not all estimates of anthropogenic aerosol forcing have been made using general circulation model (GCM) climatologies. Since sub-grid scale variation of humidity is a major uncertainty in GCMs, and as aerosol hygroscopicity and the accompanying growth are nonlinear functions of humidity (especially at relative humidities greater than 85%), this becomes an important element to consider in assessing the accuracy of the aerosol radiative forcing. Haywood *et al.* (*GRL*, **24**, 143-146, 1997) demonstrate that the impact of considering a fine spatial resolution of the humidity field versus a coarse one can lead to significant biases in the forcing estimates. It is, hence, a factor to be kept in mind when attempting to verify model estimates with observations.

GCM simulations of anthropogenic aerosol concentrations, together with a model climatology of humidities and cloud distributions, have been used to investigate the sensitivity of the (negative) hygroscopic sulfate and (positive) hydrophobic soot aerosol forcings (Haywood and Ramaswamy, *JGR*, submitted, 1997). It is found that different model simulations of the anthropogenic sulfate aerosols differ considerably in the vertical distribution despite similar column burdens. This arises due to differences in the horizontal and vertical transport of species in the various models. These differences result in varying estimates of the radiative forcing. The sulfate aerosol forcing, being largely governed by the relative humidity profile, is greater when the major portion of the columnar mass is located lower in the troposphere. In contrast, black carbon yields a greater forcing when a substantial mass is present above low clouds; then, the multiple scattering process leads to an enhancement of the absorption.

Integrating Aircraft Measurements, Satellites and Models

Antony Clarke, University of Hawaii

Assessing global radiative forcing and related climate issues depends upon analysis of validated satellite data. One approach to validation is through comparison to calibrated surface measurements (*e.g.*, AERONET), but by itself such a comparison has many ambiguities. Effective linking and interpretation of satellite observations and model simulations require knowledge of the vertical characteristics of the aerosols, implying the need for aircraft and/or lidar measurements. A strategy for integrating limited resources to best support a satellite/model validation and interpretation effort should consider the use of light 2-4 seat aircraft or remotely piloted vehicles (RPVs), which offer cheap, flexible and frequent sampling opportunities, as well as the use of traditional major aircraft campaigns.

Aircraft data need to be linked appropriately to both satellite and modeling needs. Given aerosol variability, appropriate spatial and temporal scales must be established better, as well as the most uncertain or sensitive parameters needed by the modeling community. Lidar measurements, which in the past decade have revealed complex layering of aerosols, can be especially useful for placing in situ measurements in context, thus helping to link in situ data to models and satellite retrievals. These considerations lead to a suggested strategy for enhancing the integration of models, satellite data, and other measurements [see viewgraph of Clarke in **Panel C (Strategy)**].

Aircraft data must play a role, in combination with models and satellite data, in analysis of the challenging indirect aerosol forcing issue. A large number of factors influence cloud albedo and lifetime, in addition to possible effects of aerosol perturbations, which thus complicates interpretation of even well-conceived field experiments. Anomalous aerosol conditions, as exist in large well-defined plumes (such as the volcanic plume from Kilauea, Hawaii or possibly an isolated city plume over pristine ocean) can provide exaggerated conditions to study indirect effects on clouds. It would be useful to find situations in which there is an extended persistent gradient in aerosol properties in a region with reasonably uniform cloud fields, dynamics and surface temperature. Interpretation will probably depend upon having satellite data over many years to verify the existence of statistically robust cloud effects, consistent with the notion of “events in global decadal context”.

Regional Modeling with Data Assimilation

Doug Westphal, Naval Research Laboratory

I suggest that we evaluate our ability to model aerosols (sources, transport, sinks) by applying models (global or regional) to observed events. Questions to be answered using this approach include:

1.What resolution (spatial or temporal) is required to accurately model sources, the near-source nonlinear microphysics and chemistry, and sinks (precipitation).

2. Does the dynamical model capture the characteristics of the meteorological forcing, including RH, PBL depth, precipitation, easterly waves, etc.?

3. How can we combine data from disparate satellite retrievals into a single product? What is the accuracy?

Session 5 Summary by Recorder *(Ralph Kahn)*

John Ogren *(as Facilitator)*. Regarding the link between models and observations: (1) Observations provide estimates of aerosol properties, their variability and uncertainties. (2) Models provide sensitivity of climate to aerosol properties. So the two communities must interact.

Steve Schwartz. Aerosol properties and amounts vary on the space and time scales of synoptic meteorology, which governs aerosol transports. "Averaged" values, (e.g., smoothed contours) eliminate the peaks and valleys, and are inadequate to represent aerosol non-linear effects, such as those involved in aerosol interactions with clouds. Both models and observations must capture aerosol variability on synoptic scales.

Steve Ghan. Satellite observations of radiance are usually converted to aerosol properties, which are used in a model to generate radiative forcing. This procedure involves a set of assumptions that can be avoided if model-produced radiances are compared directly to satellite-derived radiances.

Ghan also emphasized the variability of aerosols on synoptic scales.

Alan Robock. Robock recommends using the same forcing in multiple models to explore model behavior. Stenchikov and Robock developed a detailed data set of stratospheric aerosol properties and distribution for the 2-year period following the 1991 Pinatubo eruption. They produced heating rates and fluxes from the data, using the Max Planck Institute ECHAM-4 GCM. They suggest that other GCMs use these same data sets (aerosols, or heating rates and fluxes) as forcing, to allow comparison of the radiation schemes and climate response.

V. Ramaswamy. The vertical distribution of aerosols matters, e.g., for hygroscopic aerosols in a model where relative humidity varies with height, or for absorbing aerosols when there is cloud in the atmospheric column. The horizontal distribution of aerosols matters, e.g., for hygroscopic aerosols in a situation where relative humidity varies horizontally.

Ramaswamy also pointed out the danger of representing sub-grid-scale variability with "averaged" values, because of the non-linear dependence of aerosol properties on relative humidity when RH >~ 80%.

Tony Clarke. In some situations, vertically integrated aerosol properties, e.g., those measured by satellite, are related to vertically resolved properties obtained by in situ measurements - but not always. LIDAR profiles and associated relative humidity offer promising ways to establish and interpret column aerosol properties and structure.

Clarke also pointed out variability of aerosol properties on synoptic spatial and temporal scales. There are some relatively inexpensive aircraft packages to measure aerosol properties in situ. These can be used to identify the cases when surface aerosol properties are or are not representative of those in the entire column.

Doug Westphal. It is important to resolve aerosol sources and sinks at the correct scales. For example, you need the detailed, local wind pattern to understand dust sources in the Gulf of Oman region. Weekly "averaged" AVHRR aerosol retrievals show a dust "plume" off West Africa whereas the dust is actually transported in eddies mixed with clouds.

Westphal recommends an "events-based strategy" in which attention is paid to the scales necessary to resolve key attributes of the event, such as looking at "bright spot" dust sources over deserts in the TOMS daily data.

Bill Rossow. Pointed out that event-specific data handling operations may be helpful in characterizing phenomena of interest in the observations, such as studying all the easterly-phase waves off West Africa for the Sahara dust transport over the Atlantic.

SESSION 6: POTENTIAL OF SATELLITES FOR FUTURE AEROSOL DATA

(Facilitator: Bill Rossow; Recorder: Kuo-Nan Liou)

Quantitative Aerosol Data from MODIS

Yoram Kaufman, Goddard Space Flight Center

MODIS will retrieve optical thickness and aerosol size information at 10 km resolution daily globally. The size information will be detailed over oceans. Data will be gridded on one degree by one degree resolution. The mass concentrations and fluxes can be retrieved even better.

We anticipate that in the future it also will be possible to derive the single scatter albedo over land and to detect dust in the MODIS infrared channels.

Validation against aircraft data over land show errors in □ of ±0.05 ±25%. A higher accuracy is expected over ocean: ±0.03 ±15%.

Quantitative Aerosol Data from MISR

Ralph Kahn, Jet Propulsion Laboratory

Climate models now require information about the distribution of aerosol amount and type, globally, on weekly to monthly time scales -- coverage that can only be achieved with satellite instruments. However, the current operational satellite remote sensing product relies on single-angle, monospectral data, and provides only column aerosol optical depth over ocean for an assumed aerosol type.

The Multi-angle Imaging SpectroRadiometer (MISR) is scheduled for launch in June 1998 aboard the EOS AM-1 platform. MISR will simultaneously measure the upwelling radiance in 4 spectral bands (443, 550, 670, and 865 nm), at each of 9 emission angles spread out in the forward and aft directions along the flight path between +/-70.5 degrees. Global coverage will be acquired about once in 9 days at the equator; the nominal mission lifetime is 6 years.

With these data, we plan to retrieve aerosol optical depth and aerosol “type," which represents a combination of index of refraction, size distribution, and shape constraints, globally, at 17.6 km spatial resolution. According to theoretical simulations, we will retrieve column aerosol optical depth over calm ocean surfaces to an accuracy of at least 0.05 or 10%, whichever is larger, for natural ranges of aerosol type and amount, even if the particle type is not well known. In addition, three to four distinct aerosol size groups between 0.1 and 2.0 microns effective radius can be identified at most latitudes. And we can distinguish spherical from non-spherical particles under similar conditions, according to these studies (Kahn *et al.*, *J. Geophys. Res.*, in press 1997). Our sensitivity to particle composition is currently under investigation. The "at-launch" MISR algorithm will also retrieve aerosol optical depth over heterogeneous land, and surfaces covered with dense dark vegetation.

Quantitative Aerosol Data from EOSP

Michael Mishchenko, NASA Goddard Institute for Space Studies

Most current and proposed satellite remote sensing of tropospheric aerosols relies upon radiance measurements that are interpreted using algorithms that determine best fits to precalculated scattered sunlight for one or more "standard" aerosol models. However, the number of different aerosol types and their typical space and time variations can pose a severe uniqueness problem even for the multiple constraints provided by multispectral radiances of a scene at a number of observation zenith angles. We show that, in contrast, algorithms utilizing high-accuracy polarization measurements are much more sensitive to aerosol microphysics, are less dependent on the availability and use of a priori information, and can provide a physically based retrieval of aerosol characteristics (optical thickness, refractive index, and size) with accuracy needed for long-term monitoring of global climate forcings and feedbacks.

The confirmation and quantification of the Twomey effect on a global basis requires accurate satellite retrievals of CCN concentrations. Our sensitivity study shows that the AVHRR retrieval algorithm based on single-channel single-viewing-angle radiance measurements is incapable of accurately determining CCN concentrations and that an algorithm based on multiangle radiance measurements provides much better retrievals. However, even for the latter algorithm the errors in the retrieved CCN concentration can be as large as a factor of several. The poor performance of single-channel radiance-only algorithms is explained by the strong dependence of the extinction cross section and weak dependence of the phase function on aerosol effective radius. In contrast, high-precision multiangle polarization measurements are capable of constraining CCN concentrations to within a few tens of percent.

Quantitative Aerosol Data from Satellite Lidar

M. Patrick McCormick, Hampton University

A spaceborne lidar is capable of yielding tropospheric (and stratospheric) aerosol information on a global scale, with high vertical resolution (tens of meters) and a small footprint (tens to hundreds of meters). These vertical profile data greatly complement retrievals by many passive sensors (e.g., MODIS and MISR) and can be obtained even for low aerosol concentrations, thin cloud layers, and over bright surfaces. Using lidar data alone, retrievals of aerosol optical depth (AOD) are accurate to no better than 30%. For example, at an optical depth of 0.01, the lidar retrieval error is 0.003. Lidars meet the requirements set forth by a recent NRC panel convened to examine the issue of aerosol forcing for AODs less than 0.05, but not for greater values where the required uncertainty is 0.03. In order to improve the retrieval errors at the higher optical depths (values representative of many boundary layer depths), complementary information is required. Currently, lidar and a high spectral resolution oxygen A/band spectrometer seem to be the best combination for providing the required AOD information with significantly higher accuracy, over both land and water, than any other technique. For example, optical depths down to 0.02 can be retrieved with an uncertainty of about 0.005. In addition, it is recommended that future spaceborne lidars fly in a tailored orbit to optimize coincident sampling with instruments on other spacecraft such as MODIS, MISR and CERES.

Quantitative Aerosol Data from Polder

Didier Tanre, Laboratoire d'Optique Atmospherique

The POLDER (POLarization and Directionality of the Earth Reflectance) instrument is a camera composed of a two-dimensional CCD (charge coupled device) detector array with a wide FOV (field of view), telecentric optics, and a rotation wheel carrying spectral and polarized filters. POLDER was launched in August 1996 aboard the Japanese ADEOS platform and operated until the end of June 1997.

POLDER allows spectral, directional and polarization measurements with daily global coverage. One of its scientific objectives is retrieval of aerosol properties, specifically the aerosol spectal optical thickness, size distribution and refractive index.

Over ocean, the algorithm uses both the spectral dependence derived from the two near infrared channels (670 and 865 nm) and the angular information. The polarization measurements are then used for getting an estimate of the refractive index. Over land, the retrieval scheme uses the polarized channels in the three bands (443, 670 and 865 nm) over the 14 observation angles. Preliminary results show good comparisons with ground-based measurements. The expected accuracy of the optical *thickness* is about 0.05; accumulation and coarse model particles can be separated; and three classes of refractive indices, 1.33, 1.40 and 1.50, can be discriminated.

PANEL A: DIRECT AEROSOL FORCING

J. Penner (Facilitator), Y. Kaufman (Recorder), T. Nakajima, L. Stowe, I Sokolik

Panel A Summary by Recorder *(Yoram Kaufman)*

The satellite record can be used to document the spatial distribution of optical thickness and derived fluxes (which may be more accurate). Comparison with models at specific locations can reveal problems in the satellite record and models.

Field data can be used to improve the satellite inversion, even to some degree for past times.

Past data can be improved by use of several channels of TOMS and AVHRR. Note that the AVHRR and TOMS instruments need to characterized regarding their spectral response and other characteristics for the sake of long records.

There are a number of issues about the direct radiative forcing that need to be investigated, for example, the refractive index of dust aerosols.

The data record will be continued and improved with the new satellites, which can also be used for comparisons with the AVHRR and TOMS retrievals.

Yoram Kaufman suggestions are specified in the following box:

Form Forcing and Satellite Teams

1. Form teams of 10-15 scientists to deal with aerosol forcing for specific types/regions; do not separate direct and indirect effects. Use data from past concentrated field experiments (SCAR, TARFOX, ACE) for detailed information on aerosol and cloud properties. NASA can select the team leaders directly or via the NRA.
2. Form a team for analysis of satellite data, applying algorithms globally (AVHRR, TOMS, GOES/Meteosat, POLDER, OCTS, MODIS, MISR ...). There should be joint membership between this and other teams.
3. Include foreign participants, providing only travel funds.

Tasks for the Forcing Teams

1. Derive changes in aerosol forcing for the past two decades from models, with validation using satellite data and ground/air measurements. It is not clear that this is possible; let's see if good proposals are generated.
2. Derive changes in aerosol forcing for the past two decades using satellite data. Models and in situ measurements will supply coefficients in the analysis of satellite data. Derive separately the direct forcing, indirect forcing and the combined forcing, and see if they add up. Each method could be applied by different investigators. Examples of applications could include:

- Total forcing computed from the spectral angular radiance using models that convert radiance to fluxes, based on cloud coverage and surface conditions.

- Indirect forcing obtained from correlation between aerosol loading and cloud properties for several cloud temperatures. It can be derived from satellite data or from aircraft data (e.g., SCAR). Examine whether the effect on clouds has changed with time, and whether it depends on cloud type and meteorological conditions. Compute the integrated effect for each region and month.

3. Analyze new satellite data (MODIS, MISR, POLDER ... including CERES for fluxes) to derive the present forcing and its dependence on the aerosol concentration. Compare this future aerosol concentration with the results for earlier times. Check whether the processes change with time (e.g., aerosol spectral properties, cloud dependence on aerosols).

4. Analyze changes in sources with time (e.g., population, urbanization/industrialization, fire count) and the corresponding aerosol optical thickness and cloud properties.

Tasks for Satellite Teams

1. Characterize the properties of the satellite data as a function of time.

2. Develop algorithms to derive aerosol properties and cloud properties simultaneously, making use of pathfinder projects and Nakajima's effort. Apply more than one algorithm for the sake of comparison.

PANEL B: INDIRECT AEROSOL FORCING

P. Hobbs (Facilitator), S. Ghan (Recorder), T. Novakov, S. Schwartz

Panel B Summary by Recorder *(Steve Ghan)*

Uncertainty in estimates of indirect radiative forcing is far greater than uncertainty in any other anthropogenic forcing. This great uncertainty is due to the complexity of the mechanisms involved. Given the potential for a large forcing, we should not shirk the issue, but rather work hard to reduce the uncertainty.

To reduce the uncertainty, an experiment should be designed involving a signal that is characteristic of anthropogenic aerosol (e.g. a small town). A well-designed experiment of this type, involving satellite as well as in situ measurements, and closely linked to improving and evaluating both process models and GCMs, offers the potential to obtain for the first time a quantitative estimate of indirect forcing by anthropogenic aerosols. The experiment should isolate the forcing into at least three factors: (a) the sensitivity of aerosol concentration, composition, and size distribution to emissions, (b) the sensitivity of droplet number to aerosol concentration, composition, and size distribution, and (c) the sensitivity of cloud radiative forcing to cloud microphysical parameters.

We envisage a highly focused experiment, similar in scope to the highly successful (and relatively cheap) TARFOX. Satellite data would be used to identify a geographical location where anthropogenic emissions commonly give rise to the situation depicted schematically in the box on the following page. That is, emissions from a town or city cause stratiform clouds downwind to have a greater albedo than the surrounding clouds, due to the effects of the emissions on cloud microstructure (similar to the "ship track" effect, but on a larger scale). Airborne studies would then be carried out at the site to quantify the nature of the anthropogenic emissions and their effects on cloud structure. Based on these observations, parameterizations of the effects of aerosols on cloud albedo would be developed for inclusion in GCMs.

See http://www.giss.nasa.gov/meetings/aerosols97/panelb.GIF

Schematic of suitable site for field experiment to quantify indirect radiative forcing by aerosols

PANEL C: STRATEGY

J. Hansen (Facilitator), M. Prather (Recorder), A.Clarke, R. Kahn, V. Ramaswamy

Recorder and Facilitator Notes

Hansen reviewed objectives: How can we use satellite data, global models and analysis to advance our understanding of aerosol (direct and indirect) climate effects?

The focused workshop target is quantitative definition of the global distribution of aerosol (direct and indirect) radiative forcing for the period of satellite data (1979-present-near future) using satellite data, modeling/analysis and whatever else is available.

The short-term product of the workshop will be guidance for an NRA (NASA Research Announcement) for research/analysis to achieve this objective.

Desired longer-term outcomes include:

1. Bright ideas (strategy) on how to quantify (and confirm) aerosol climate forcing.

2. Productive interactions/cooperations between specialized groups [satellite <=> global modeling <=> in situ data <=> small scale modeling].

3. Interagency coordination/cooperation.

Hansen also mentions the “events” or, more accurately, the “events in global decadal context” strategy (see following viewgraph). This is based on the hypothesis that several aerosol forcings may be sufficiently large to have detectable influences on regional or global climate. Examples of these forcings are large volcanos such as Pinatubo, soil dust outbreaks, biomass burning, and regional industrial plumes. Thus the approach in this strategy is to quantify such aerosol distributions and their impact on climate parameters. This must be done in the context of a climate record of sufficient length to define the influence of unforced (chaotic) variability of climate parameters; also the record length should force models to be general, i.e., avoid curve-fitting to a single event. The period of satellite data, now approaching 20 years, provides an excellent opportunity for this strategy. The single most important data set for this period that is not yet available is the 4-D temperature field, which can be extracted from infrared meteorological sounding data (TOVS).

“Events in Global Decadal Context” Strategy

1. Use satellite data + aerosol models + whatever else available to define estimated distributions of aerosol forcings in the period 1979-present. [change vs. time of stratospheric aerosols, tropospheric sulfates, soil dust, biomass burning, carbonaceous and total aerosols]

2. Make these available to climate research community; global climate models used to generate expected (regional, vertical, seasonal) signatures of the aerosol forcings.

3. Check simulations against global observations including temperatures measured by satellites and radiosondes, and also against other global data such as observed cloud particle size variations.

Notes:

1. Possible fly in ointment: correlation of other forcings with aerosols. This may not be a major problem, because of the large magnitude of aerosol forcing, but at least we should be concerned about tropospheric ozone.

2. It remains to be shown that this can be accomplished for all the major tropospheric aerosols (soil/dust, sulfates, carbonaceous aerosols).

3. Someone needs to produce 4-D temperature fields from meteorological sounder data.

Ramaswamy said that much can be done with existing satellite data, and specifically seconds the importance of the 4-D temperature from sounders. We should try to put together a first order record of climate forcings and climate parameters, including temperature, water vapor, clouds and aerosols, for this period. He suggests that we begin with a focus on "dust", which clearly is visible to satellites, occurs in large "events", and is perhaps simpler than some other aerosols. Can we document the change in climate forcing by dust over the past two decades? Ramaswamy also mentions the need to try to separate natural and anthropogenic contributions to the soil aerosol forcing, as IPCC, for example, wants to define the anthropogenic component.

Clarke recommended focusing on specific regions, after establishing goals and objectives that help to identify appropriate study regions. An example is the schematic region used by Hobbs [see Panel B] to discuss a possible experiment to study indirect aerosol effects. Clarke suggests that this might be done before global studies. Prather pointed out that it will be important to include chemistry and related source gases in such regional studies. Clarke's suggestions regarding strategy are summarized on the following chart.

Suggested Strategy to Enhance Satellite-Model-In Situ Data Integration

1. Identify a few optimum regions for satellite/model comparisons, where:

A well-defined "event" can be studied (dust outbreaks, biomass plumes, anthropogenic plumes, volcanic sources, etc.)

Satellite coverage is optimum (signal/noise, digitization, spatial averaging)

Meteorology is predictable and station data (profiles) exist at several points in region

Models are well characterized (minimal sub-grid phenomena, etc.)

Ground based measurements might best reflect column properties

Lidar is available for regular assessment of aerosol structure

Logistical needs for occasional aircraft studies can be met

Possibly representative aircraft measurements may already exist

2. Focus airborne measurements in these optimum regions:

Encourage aircraft and other satellite validation programs to include these prescribed regions

Expand support for low-cost light aircraft instrument packages and RPVs

Involve satellite analysts and modelers in aircraft missions to ensure appropriate sampling

Link spectral lidar and aircraft aerosol measurements to improve quantitative interpretation

Establish common data archiving protocol for NASA and other programs for use by modelers

Kahn discussed elements that he felt should be included in the strategy. His main point was that the goal of obtaining an aerosol climatology requires an ISCCP-like project that would integrate satellite and in situ data into the best possible constraints on aerosol amount and type. This could be done with retrospective data, and should also be done with new data. The project would need a PI with the responsibility of making tough decisions about how to weight different observational constraints, and how to combine them into a meaningful product. The PI would need to have an appreciation for statistics and data handling issues, and a deep understanding of aerosol modeling and observations. He mentioned that we should make use of related ground-based records such as atmospheric extinctions measured at astronomical observatories and aerosol depositions in ice cores, establish a “best” albedo (and changes) for the globe, and establish a column water vapor “climatology”. He also noted the problems in aggregating fractal scales and comparing non-aligned co-data sets. Laboratory experiments on aerosols and clouds are a potentially very valuable source of information, which unfortunately is being largely ignored. His discussion is summarized on the following viewgraph.

Comments on Strategy

1. What’s the best we can hope to do, 1979-present?

Collect a data base of field measurements from 1979-present (there are about 1200 papers/year with some kind of constraint on aerosol properties). ISCCP-like project.

Need standards for measurements — e.g., over solar spectrum; formats; units

Think of additional (surrogate) data sources for aerosol production (records of astronomical viewing at desert sites?), loss, microphysical properties (sedimentary deposits?), radiative impacts, effects on clouds.

Best guess at surface albedo climatology — need both this and single scatter albedo to determine if dust is warming or cooling.

Try 2-channel AVHRR retrieval of aerosol optical depth, using column water vapor.

Try DDV and dark inland water retrievals of aerosol optical depth using surface albedo climatology.

[The mathematics of creating climatologies (i.e., creating Level 3 data sets from Level 2 data sets) could use more thought.]

Use in situ data base to validate satellite retrievals and trends, to the extent possible.

Use satellite and in situ data to critically test (“validate”) the models, where possible.

[The mathematics of "validation", i.e., comparing Level 2 data sets, could use more thought.]

--- Bits of these have already been done.

2. Future climatologies can benefit from:

More "closure experiments" - designed to test whether measurements are self-consistent.

More space-time correlation studies — e.g., times known to have high winds in desert regions; "holidays" when and where factories and cars operate less for a week or so — measure the change in aerosol amount on a regional basis to get estimate of aerosol flux (e.g., Thanksgiving, July 4, holidays in other parts of world).

3. Indirect effects — lab experiments (e.g., cloud chambers)

Prather suggests consideration of the following strategy sequence:

1. Define homogeneous record of aerosols and clouds for 1980-present. Store as "radiances" or a similar quantity that is independent of the aerosol-model assumptions used in retrievals. For example, do not report aerosol "optical depth" based on irradiance measured at a single wavelength. [The comment was made that yes, it is desirable to avoid a model-dependent "archive", but users will want more geophysical quantities than just the spectral irradiance. Another comment was that yes, we need to have aerosols and clouds together, for aerosol production/loss terms and for analyzing indirect effects.] Although the emphasis should be on a long (approximately 20 year) record, it would be useful to have subperiods with more intensive detailed data, for example, the period with POLDER data.

2. Develop models with all aerosol (and cloud) components in order to predict the "record" of radiances, aerosols, clouds, etc. This requires a parallel record of analyzed meteorological fields to run chemistry/aerosol transport models. Climate models (e.g., forced by observed SSTs and aerosol/cloud radiative forcings) also may be useful.

3. Use these model and data records to test simulation of: a) long term changes over the period of record, b) variability (synoptic to seasonal), c) examine for notable "goofs", e.g., under or over prediction of aerosols.

4. Use the above comparison to identify locales for "process" studies for today's atmosphere, checking identification of sources and mechanisms.

Other specific comments by Prather re an "events" strategy

Focus should be on radiative properties in the above comparison of models and data records; other physical properties are needed to understand mechanisms, but not for the climate forcing.

Is it possible to measure directly the radiative forcing over some of the "hot spots" of aerosol activity?

Interactions between gas-phase chemistry and different aerosol types is important in planning "process" studies.

The upper troposphere was neglected in our discussions, as we did not discuss the potential of SAGE (or CCOSM) for the upper troposphere. Perhaps this was because relevant people were at a concurrent "cirrus" workshop, but this neglect may need to be redressed.

PANEL D: AGENCY PLANS

R. Curran, J. Levy, J. Moyers, R. Petty, R. Ferek

Curran summarized the NASA *Strategy to Address the Effects of Aerosols on the Global Environment*, which is an appendix to the NASA *Science Research Plan*. NASA already has substantial aerosol research which includes consideration of both climatic and chemical aerosol effects, and including both stratospheric and tropospheric aerosols. NASA's aerosol research is supported primarily by the Office of Mission To Planet Earth (MTPE), specifically by: 1) science division research and analysis programs and EOS interdisciplinary investigations, 2) flight mission project science support [presently UARS, SAGE, TOMS and EOS], and 3) focused research to understand the impact of aircraft on the environment, jointly sponsored with the Office of Aeronautics.

The present workshop is intended to help define a focused initiative that would improve understanding of radiative forcing caused by aerosols. This initiative would be coordinated with and draw upon the aerosol research already sponsored by NASA. It would be expected to make effective use of the relevant global satellite measurements and interdisciplinary investigations supported by NASA. Because of the complex and subtle ways that aerosols can influence climate, a successful research program will undoubtedly require cooperation among federal agencies and also international cooperation.

Levy summarized the Aerosol Program within the Climate and Global Change Program of the National Oceanic and Atmospheric Administration (NOAA). The objective of this program is predictive understanding of the influence of tropospheric aerosols on the Earth's chemical and radiative balance, with a view towards the following near-term information needs: 1) attribution of climate change (Have you seen anything yet? - unmasking the greenhouse gas signal), 2) prediction of future climate scenarios ("What are our best options?"). The expected deliverable is improved detection/attribution/prediction for IPCC (2000).

The goals are 1) reduced uncertainty in the (calculated) magnitude and geographical distribution of radiative forcing due to aerosols, obtained via long-term monitoring of chemical, physical, and optical properties at selected sites, closure studies as part of intensive field campaigns, monitoring, and laboratory studies, and modeling, 2) improved understanding of the processes that link emissions of aerosols precursors to the spatial distributions, abundances, and properties of aerosols obtained via field measurements (ground, air, ship, satellite) and modeling. Among these activities monitoring at selected sites field measurements from ships are NOAA specialties.

The objectives of the NOAA Aerosols Program are central to the objectives of the current workshop. But possible NOAA contributions are constrained by the level of support for this program, which is $1M per year and is not expected to increase.

Petty summarized the Department of Energy's aerosol research program, which is sponsored by its Atmospheric Chemistry Program (ACP), Atmospheric Radiation Measurement (ARM) program, and the National Institute on Global Environmental Change (NIGEC). DOE specifically supports research to understand the fundamental scientific phenomena associated with aerosol radiative forcing and climate change.

These studies are expected to include research on aerosol forcing of climate that advances knowledge in the representation of aerosols in global climate models, particularly with respect to indirect climate effects; laboratory and theoretical research on aerosol optical properties; identification of aerosol molecular composition particularly the organic fraction; development of an understanding of aerosol formation and growth in the atmosphere; studies elucidating the aerosol-CCN-cloud droplet-albedo relationship; execution of atmosphere closure experiments to test theoretical understanding; application of instrumentation technology for measuring aerosol properties in situ; and system integration and assessment utilizing sensitivity/uncertainty analyses.

The DOE research agenda is central to objectives of the current workshop. But new contributions by DOE are constrained by research budgets that are expected to at best hold steady.

Ferek summarized the aerosol research of the Office on Naval Research which is funded within three programs: Marine Meteorology and Atmospheric Effects (322MM), Environmental Optics (322OP), and Biological and Chemical Oceanography (322BC). The Navy's interests lie primarily in the effects of aerosols on propagation of electro-optical radiation (visible and infrared). While not specifically driven by the issue of aerosol radiative forcing, much of the same physics is involved, particularly with fine particles and visible radiation. Specific interests, somewhat special to the Navy but overlapping with the other agencies' interests in the direct forcing issue, involve marine and coastal aerosols, near-surface natural and anthropogenic aerosols, desert dust in coastal regions, retrieval of boundary layer aerosol properties by remote sensing, and effects of coarse mode, short-lived aerosols on infrared wavelengths. ONR seeks to develop a predictive capability which will require at least four components to achieve success: *model initialization* (perhaps through remote sensing techniques), *aerosol transport modeling* (currently an active area of research using operational Navy meteorological models), *aerosol process modeling* (incorporating physical and chemical transformations), and *extinction calculations* across the range of wavelengths from the visible to infrared.

The funding available for basic aerosol research is currently about $1.4M per year, but the program is constrained by decreasing Department of Defense funding of basic R&D, and it has declined about 10% per year for the last two years. Funding appears likely to remain level or decrease slightly for the next several years.

Participants of the NASA GISS Aerosol/Climate Workshop
June 2-3, 1997

NAME:	**Affiliation**	**E-Mail**	**Phone**	**Fax**
Ackerman, Andrew	NASA ARC	ack@sky.arc.nasa.gov	415/604-3522	3625
Bergman, Kenneth	NASA HQ	kbergman@hq.nasa.gov	202/358-0765	2770
Bevilacqua, Richard	NRL	bevilacqu@map.nrl.navy.mil	202/767-0768	7885
Bhartia, Pawan	NASA GSFC	bhartia@chapman.gsfc.nasa.gov	301/286-4094	1662
Carlson, Barbara	NASA GISS	bcarlson@giss.nasa.gov	212/678-5538	5552
Chuang, Cathy	LLNL	chuang1@llnl.gov	510/423-2572	4908
Clarke, Tony	U. Hawaii	tclarke@soest.hawaii.edu	808/956-6215	
Curran, Bob	NASA HQ	rcurran@hq.nasa.gov	202/358-1432	554-6499
Durkee, Phil	Naval Post Grad. School	durkee@nps.navy.mil	408/656-3465	3061
Erlick, Carynelisa	U. Chicago	erlick@rainbow.uchicago.edu	773/288-3857	702-9505
Ferek, Ron	ONR	ferekr@onr.navy.mil	703/696-0518	3390
Ghan, Steve	Pacific NW Labs	sj_ghan@pnl.gov	509/372-6169	2887
Han, Qingyuan	U. Alabama/Huntsville	han@atmos.uah.edu	205/922-5785	5755
Hansen, Jim	NASA GISS	jhansen@giss.nasa.gov	212/678-5619	5622
Herman, Jay	NASA GSFC	herman@tparty.gsfc.nasa.gov	301/286-7821	1662
Hobbs, Peter	U. Washington	phobbs@atmos.washington.edu	206/543-6027	685-7160
Kahn, Ralph	JPL	ralph.kahn@jpl.nasa.gov	818/354-9024	393-4619
Kaufman, Yoram	NASA GSFC	kaufman@climate.gsfc.nasa.gov	301/286-4866	1759
Lacis, Andy	NASA GISS	alacis@giss.nasa.gov	212/ 678-5595	5552
Lee, H.N.	EML	hnlee@eml.doe.gov	212/620-6607	
Leifer, Robert	EML	Rleifer@eml.doe.gov	212/620-3626	3624
Levy, Joel	NOAA OGP	levy@ogp.noaa.gov	301/427-2089x21	2082
Liou, Kuo-Nan	U. Utah	knliou@climate.utah.edu	801/581-3336	585-3681
McCormick, Pat	Hampton U.	mcc@hamptonu.edu	757/728-6867	727-5090
Mishchenko, Michael	NASA GISS	mmishchenko@giss.nasa.gov	212/678-5528	5552
Moyers, Jarvis	NSF	jmoyers@nsf.gov	703/306-1522	0377
Nakajima, Teruyuki	U. Tokyo	teruyuki@ccsr.u-tokyo.ac.jp	81-3-5453-3959	3964
Novakov, Tica	U. Cal. Berkeley/LBNL	Tnovakov@lbl.gov	510/486-5319	4733
Ogren, John	NOAA CMDL	johno@cmdl.noaa.gov	303/497-6210	6290
Penner, Joyce	U. Michigan	penner@umich.edu	313/936-0519	764-5137
Petty, Rick	DOE	rick.petty@oer.doe.gov	301/903-5548	8519
Prather, Michael	U. Cal. Irvine	mprather@uci.edu	714/824-5838	3256
Prospero, Joseph	U. Miami	jprospero@rsmas.miami.edu	305/361-4789	
Ramaswamy, V.	NOAA GFDL	vr@gfdl.gov	609/452-6510	987-5063
Randall, Cora	U. Colorado	cora.randall@lasp.colorado.edu	303/492-8208	6946
Robock, Alan	U. Maryland	alan@atmos.umd.edu	301/405-5377	314-9482
Rossow, Bill	NASA GISS	wrossow@giss.nasa.gov	212/678-5567	5622
Schwartz, Steve	DOE Brookhaven	ses@bnl.gov	516/344-3100	2887
Seinfeld, John	Cal Tech	john_seinfeld@starbase1.caltech.edu	818/356-4635	585-1729
Sokolik, Irina	U. Colorado	sokolik@alcor.colorado.edu	303/492-5724	6946
Stenchikov, Georgiy	U. Maryland	gera@atmos.umd.edu	301/405-5370	314-9482
Stowe, Larry	NOAA NESDIS	lstowe@orbit.nesdis.noaa.gov	301/763-8053	8108
Tanre, Didier	Lille, France	Didier.Tanre@univ-lille1.fr	333-203-37033	20434342
Tegen, Ina	NASA GISS	itegen@giss.nasa.gov	212/678-5573	5552
Thompson, Anne	NASA GSFC	thompson@gator1.gsfc.nasa.gov	301/286-2629	1754
Travis, Larry	NASA GISS	ltravis@giss.nasa.gov	212/678-5999	5622
Turner, Robert	Sci. Appl. Int'l Corp.	turnerr@cpva.saic.com	408/649-5242	8048
Uematsu, Mitsuo	U. Tokyo	uematsu@ori.u-tokyo.ac.jp	81-3-5351-6533	6533 (same)
Westphal, Doug	NRL	westphal@nrlmry.navy.mil	408/656-4743	4769
Winker, David	NASA LaRC	d.m.winker@larc.nasa.gov	804/864-6747	